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Energy Procedia 57 (2014) 2295– 2304

Energy Procedia

2013 ISES Solar World Congress

Validation of the simulation of solar air collector prototypes.

E. Villanueva Vega[a]*, F. Noh-Pat[a]

[a]*Universidad Autónoma de Baja California, Boulevard Universitario No. 1000, Tijuana C.P. 21500, México*

Abstract

The solar air systems can be appropriated into constructions due to the easy integration of air collectors in building facades, either into walls and roofs or by replacing one of them. There are several types of solar air collectors, which differ from each other on how the cover, absorber and airflow pattern are laid out in the collector. It is important to know the collector performance in order to design other system elements.

Designs of solar air collectors and their respective models can be found in some solar engineering books. The model equations allow measuring the collector performance at a particular time. However, it is necessary to know some state variables of the collector such as the collector element temperatures, and heat transfer coefficients. It is important to emphasize that the collector state variables are changing with time due to the environmental effects.

This study deals with the mathematical models, the implementations and the validations of numerical simulation for three experimental prototypes of solar air collector. The Solar-Institute Jülich of Germany developed the prototypes.

In a general form the mathematical one-dimensional transient model of heat flux of each solar air collector is presented. Besides, the implementation of the collector models in the MATLAB-Simulink software is described.

As a result of the validation of experimental data, the mathematical models and numerical implementations are able to estimate the air temperature inside of the collector. Average absolute error between integrals of simulated and measured temperatures reached hardly 1.2°C. In general, the three solar air collector models had a very good performance.

Selection and/or peer-review under responsibility of ISES.

Keywords: Solar air collector; prototype; mathematical model; collector block; transient; heat flux; implementation; simulation; software; Matlab; Simulink; validation.

* Corresponding author. Tel.: +52-664-179-8988; fax: +52-664-906-1534.
E-mail address: eric.villanueva@uabc.edu.mx .

1876-6102
Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.237

1. Introduction and goals

Buildings in cold climates, one of the largest forms of energy consumption is water and space heating. For example, German private households spent 81.7% of the final energy consumption on water and space heating in 2011 [[3]. The heat distributed throughout the building can be produced by solar energy or another energy source. Solar technology is an option for satisfying part or the entire heating requirement in a building, particularly with a solar air system where air is the working fluid.

There are several types of solar air collectors, which differ from each other on how the cover, absorber and air flow pattern are laid out in the collector. It is important to know the collector performance in order to design other system elements such as the fan [[4, [6].

Designs of solar air collectors and their respective models can be found in some solar engineering books, e.g. [[4, [5, [7, [8, [11]. The model equations allow measuring the collector performance at a particular time. However, it is necessary to know some state variables of the collector such as the collector element temperatures, and heat transfer coefficients. It is important to emphasize that the collector state variables are changing with time due to the environmental effects.

The application of a solar air system shows great promises. Nowadays computer simulations can allow developing, optimizing and testing the solar air collector. Moreover, it makes possible to evaluate the solar air system feasibility and lead to optimized system designs.

The main aims of this study were to develop mathematical models for three experimental prototypes of solar air collectors, to make implementations of these mathematical models in software (collector blocks), and to validate the numerical simulation of the collector blocks. The mathematical models are based on solar air collector prototypes designed by the Solar-Institute Jülich. The mathematical models and collector blocks were developed to take into account the following characteristics:

- A collector constructed of different materials
- A collector with others magnitudes
- A collector with a different surface position.

2. Basics for the mathematical model of solar air collector

2.1. Prototypes of solar air collectors

The following solar air collector prototypes were designed by Solar Institute Jülich and the company Fischer GmbH in the project called "Entwicklung und Optimierung der Einsatzmöglichkeiten einfacher solarer Luftkollektoren aus bestehenden Fassadenkollektoren im Industriehallenbau" from 01.09.2003 to 28.02.2005.

- Underflow collector: It has an enclosed space or air gap between the cover and absorber, which has the function of heat insulation (see Fig. 1). The airflow passes under the absorber and thus only one absorber side transfers heat to the air flow. Additional collector construction details are given by Table 1.

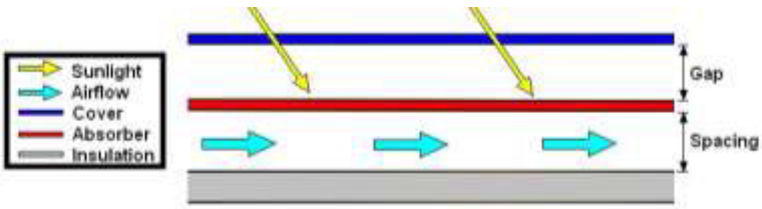

Fig. 1. Longitudinal section of the underflow collector.

Table 1. Details of the underflow collector prototype.

Item	Description
Cover	Polycarbonate. Trade name: Makrolon mono long life clear 2099
Absorber	Sheet steel type S-GD with coating
Insulation	Polyurethane rigid foam with a cover of plastic coated steel sheet. Trade name: FischerTHERM LL100
Collector dimensions	0.88 x 8 m
Gap	0.015 m
Spacing	0.015 m

- Uncovered underflow collector: It does not have any cover and thus the absorber surface is in contact with the surroundings (see Fig. 2). The airflow passes through the spacing between the insulation and the absorber where it is heated. Additional collector construction details are given by Table 1.

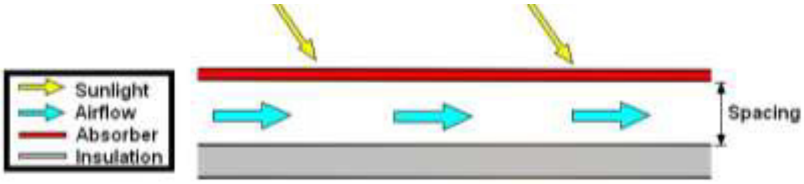

Fig. 2. Longitudinal section of the uncovered underflow collector.

- Overflow collector: In this collector, airflow passes through the spacing between the cover and the absorber (see Fig. 3). The absorber is lying on the insulation, so that only one absorber side transfers the heat to the flow. Additional collector construction details are given by Table 1.

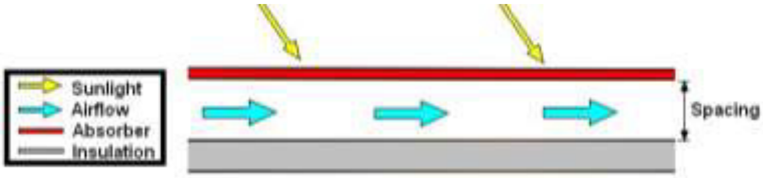

Fig. 3. Longitudinal section of the overflow collector.

2.2. Computer software for running the models

MATLAB-Simulink software [[9] makes easy the design, simulation and analysis of dynamic processes depending on time by using interactive graphical blocks from a set of block libraries. Each block is an operator in a black box. Moreover, Simulink allows replacing a set of blocks with a single block by using subsystems. The subsystems are useful for defining hierarchical and simple models.

One additional extension for Simulink is CARNOT Blockset [[10], which has been created for thermal engineering systems. Data vectors are the main data structure used by CARNOT Blockset. In particularly, the Thermo-Hydraulic Vector (THV) and weather data vector are specified in a certain format. The THV has the data about the actual state of the working fluid and the weather data vector has the information of the atmospheric condition for the simulation period.

In general, the THV gets into a block where one or several physical values of the working fluid are used for calculations. Inside there are calculations having an effect on some physical values which are modified. Afterwards the remaining and new physical values are gathered, the block is left. Then the THV can be used as an input for a next block. Each component of the heating system has at least one THV access for connecting with another system component.

3. Thermal engineering for the mathematical models of solar air collectors

In this paper, we only develop the most complex mathematical model of solar air collector due to the amount of equations used on each one. It is the underflow collector.

3.1. Basics and general assumptions

General assumptions are one-dimensional heat flow through the collector elements and negligible absorbed solar radiation by the cover and insulation.

For a better accuracy of the model equations, the collector is divided in sections. Except for the extreme sections of the collector, the collector sections are assumed to be symmetric. The outlet values of one collector section are the inlet values for the next collector section.

3.2. Heat flux balance equations and useful heat flux

The air collector simulation means a dynamic process or an unsteady energy balance due to many parameters changing with time such as the weather data and temperatures of the collector components. Hence, heat flux balance equations are used for the model development. They are expressed with time-dependent ordinary differential equations and referenced per unit area for simplicity and convenience.

Consider an energy balance for a solar air collector in steady state. The absorbed solar radiation is the collector input energy which is transferred through its components. The part of heat leaving the collector to the environment is considered as a thermal loss and the transferred part to the air flow as useful heat [[7, [8].

The heat flux balance of the collector is based on the balance of its components. The useful heat flux is the heat flowing from the components to the air flow per unit area. Now consider a simple heat flux balance for an element. The stored heat flux changes the element temperature and the other part is transferred to a surrounding element or leaves the collector in form of thermal losses.

Equation (1) expresses a simple heat flux balance of an element where the input heat flux is the sum of the stored part and the conducted part. The conducted heat per unit area flows from an element towards the surroundings by conduction, convection and/or radiation.

$$\dot{q}_{\mathrm{stored}} = \dot{q}_{\mathrm{input}} - \dot{q}_{\mathrm{conducted}} \tag{1}$$

The following equation (2) expresses the amount variation of heat stored with time in an element per unit area. It is described as a function of temperature changing over a time interval.

$$\dot{q}_{\mathrm{stored}} = \frac{dq_{\mathrm{stored}}}{dt} = \delta \ \ \rho \ \ c_p \frac{dT}{dt} \tag{2}$$

By substituting equation (2) into Equation (1) and isolating the term dT/dt, it yields to equation (3) which is a general heat flux balance for an element.

$$\frac{dT}{dt} = K\left[\dot{q}_{input} - \dot{q}_{conducted}\right] \tag{3}$$

where the steady-state gain *K* is defined [[12] as

$$K = \frac{1}{\delta \ \rho \ c_p} \tag{4}$$

The amount of heat transferred convectively from a component into the air flow is a heat contribution to the collector useful heat flux:

$$\dot{q}_{useful} = \sum_{x \in \{a,c,i,ei\}} \dot{q}_{x-f} \tag{5}$$

The subscript *x-f* means between element *"x"* and the air flow. The terms a, c, i, ei means absorber, cover, insulation and edge insulation respectively.

The heat flux balance of the underflow collector is a system of three differential equations (6). The system describes the temperature changes in the absorber, cover and insulation layer. The subscript *amb* means ambient or environment.

$$\begin{cases} \dfrac{dT_a}{dt} = K_a\left[\dot{q}_{solar} - \dot{q}_{a-c} - \dot{q}_{a-i} - \dot{q}_{a-f}\right] \\ \dfrac{dT_c}{dt} = K_c\left[\dot{q}_{a-c} - \dot{q}_{c-amb}\right] \\ \dfrac{dT_i}{dt} = K_i\left[\dot{q}_{a-i} - \dot{q}_{i-amb} - \dot{q}_{i-f}\right] \end{cases} \tag{6}$$

where K_x is the steady-state gain of the absorber, cover or insulation, according to the case. From equation (5), the useful heat flux of the collector section yields:

$$\dot{q}_{useful} = \dot{q}_{a-f} + \dot{q}_{i-f} \tag{7}$$

3.3. Calculations of heat fluxes

The absorbed solar radiation per unit area ($\dot{q}_{solar}$) is the input power in a solar air collector. Except for the uncovered underflow collector, the heat flux is calculated by a CARNOT block called *collector optics.*

Due to convenience and simplicity, the thermal resistance concept is used for the other heat flux calculations. This concept is an analogy of heat flux as electric current flow [[13]:

The equations of heat flux calculations for underflow collector are given by Table 2.

Table 2. Heat flux calculations for underflow collector.

Heat flux between:	Equation
absorber and cover $\dot{q}_{a-c}$	This heat flux equation has thermal resistance network of two-parallel resistances. $\dot{q}_{a-c} = (h_{rad} + h_{nat})(T_a - T_c)$ (8) where $h_{rad} = \frac{\sigma\,(T_a + T_c)\,(T_a^2 + T_c^2)}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_c} - 1}$ (9) The term h_{nat} is a natural-convection heat transfer coefficient given in references' subjects [[13,[14].
absorber and insulation $\dot{q}_{a-i}$	The equation has only a thermal resistance for radiation due to the air flowing between the collector elements. $\dot{q}_{a-i} = h_{rad}\,(T_a - T_i)$ (10) where $h_{rad} = \frac{\sigma\,(T_a + T_i)\,(T_a^2 + T_i^2)}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_i} - 1}$ (11)
absorber and air flow $\dot{q}_{a-f}$	This equation has only a thermal resistance for convection and it is expressed as: $\dot{q}_{a-f} = h_f\,(T_a - T_f)$ (12) where h_f is the convection heat transfer coefficient between one collector element and air flow. It is calculated according to Pottler [[15].
cover and ambient $\dot{q}_{c-amb}$	The heat flux equation has thermal resistance network of two-parallel resistances. $\dot{q}_{c-amb} = (h_{rad} + h_w)(T_c - T_{amb})$ (13) where the term h_{rad} is $h_{rad} = \frac{\sigma\,\varepsilon_c\,(T_c + T_{sky})(T_c^2 + T_{sky}^2)(T_c - T_{sky})}{T_c - T_{amb}}$ (14) and h_w is the convection heat transfer coefficient between the cover and the environment [1] is given by: $h_w = 5.7 + 3.8\,V_w$ (15)
insulation and air flow $\dot{q}_{i-f}$	This equation considers the edge heat contribution which is referenced to the unit area for a rough calculation. $\dot{q}_{i-f} = (h_f + f_{As}\,h_f)\,(T_i - T_f)$ (16) where h_f is the same coefficient used in Equation (12) and f_{As} is the area correction factor in spacing defined as: $f_{As} = \frac{A_{edge\ in\ spacing}}{A}$ (17)

insulation and ambient $\dot{q}_{i-amb}$

The heat flux equation considers only a thermal resistance for conduction. The effective thermal resistance for convection and radiation are very small compared with the conduction resistance [[7].

$$\dot{q}_{i-amb} = \left(\frac{\lambda_i}{\delta_i} + \frac{f_{Ai}\,\lambda_i}{\delta_{ei}}\right)(T_i - T_{amb}) \tag{18}$$

where f_{Ai} is the area correction factor of the edge in spacing and gap defined as:

$$f_{Ai} = \frac{A_{edge\ in\ spacing\ and\ gap}}{A} \tag{19}$$

3.4. Important parameter for testing the collector models

A solar air collector is designed to convert solar radiation into useful power gain. The useful power gain in a collector section is determinate to be

$$\dot{Q}_{useful} = (b\ l)\ \dot{q}_{useful} \tag{20}$$

where b is the width of the collector and l is the length of the collector section.

This gain consists of the amount of heat transferred from the collector components into the airflow. This means that the temperature of the airflow rises during a certain time interval. Therefore, the outlet airflow temperature is one reference parameter of the collector performance [2].

$$T_{f\ out} = \frac{\dot{Q}_{useful}}{\dot{m}\ c_{p\ f}} + T_{f,in} \tag{21}$$

where the terms $T_{f,in}$ and $T_{f,out}$ are the inlet and outlet airflow temperature, respectively.

4. Blocks of solar air collector in Simulink with CARNOT Blockset

In the constructions of collector blocks are considered that the mathematical models use values of air properties such as Reynolds number, Prandtl number, density, specific heat, etc. They are calculated by CARNOT functions, which have the limitation for an air pressure of 0.1 MPa.

Fig. 4. Blocks of solar air collectors.

The blocks of the collectors can be used in the same way as CARNOT blocks. The air collector blocks follow the patterns of the regenerative blocks in CARNOT Blockset. They are masked blocks with the same colors, geometries and ports as those of *collector_flat_plate* block and *collector_parabolic_trough* block.

Each block of collector model has three inlet ports and one outlet port for input and output vectors: The Weather data vector is input in the weather port , the collector position vector is connected to the position port, the THV enters and exits the collector block through the THVin and THVout ports, respectively.

All the collector blocks have a mask which displays information about the collector in the dialog box and the collector parameters to be specified by the user. The basic parameters to be specified are: Collector gross length, gross width, air channel depth, optical efficiency, leakage and Initial temperature, thickness, density, specific heat capacity and emissivity of the absorber, insulation and cover, thermal conductivity of the insulation, thickness of the edge insulation.

In a real collector, there is undesired leakage of air from the airflow passage. Air leakages can affect the collector performance [[4]. Therefore, the parameter Collector leakage is placed in the collector mask. The parameter is assumed to be constant along the gross length of the collector [[11].

5. Blocks' validation of the solar air collector

5.1. Methodology

The air temperature difference between the collector entrance and the exit is a parameter for evaluating the performance of solar air collectors [[4, [7]. Hence, the blocks of the collector are tested by comparing the simulated airflow temperatures with measured temperatures of the collector prototypes.

In order to test the blocks of collector models, it was necessary to determine some missing data in the records, which are used as input data for the simulation:

- First, the temperature data contain four different values which correspond to the inner collector. However, the measured temperature at the collector inlet and outlet are not available in the record.
- Second, the data contain values for the total solar radiation, ambient temperature, wind speed and mass flow rate of air at the collector inlet. However, basic weather-related values such as sky temperature, incidence angle, diffuse and direct radiation on collector surface, are missing.

Each block of the collector models was set up for simulating a collector prototype. In the block mask, parameters of the prototype design and properties of the construction elements were specified. Air-tight collectors are difficult to construct and the collector prototypes were not an exception, since it was sealed with wood and silicone. Hasting and Mørck [[4] state that for glazed air collectors, the air leakage rates are as high as 10% depending on the static pressure.

5.2. Simulation results of the solar air collector prototypes and conclusions.

After simulation, the simulated and measured temperatures at seven meter through the collector were put into a graph and analyzed. Despite that some parameters were determined and the normal uncertainty of measurements, the temperature differences were small and could be satisfactorily explained. Average absolute error between integrals of simulated and measured temperatures reached hardly 1.2°C. The relative errors of the integrals were between 0.9% and 4.5%. In general, the three blocks of solar air collector models had a very good performance.

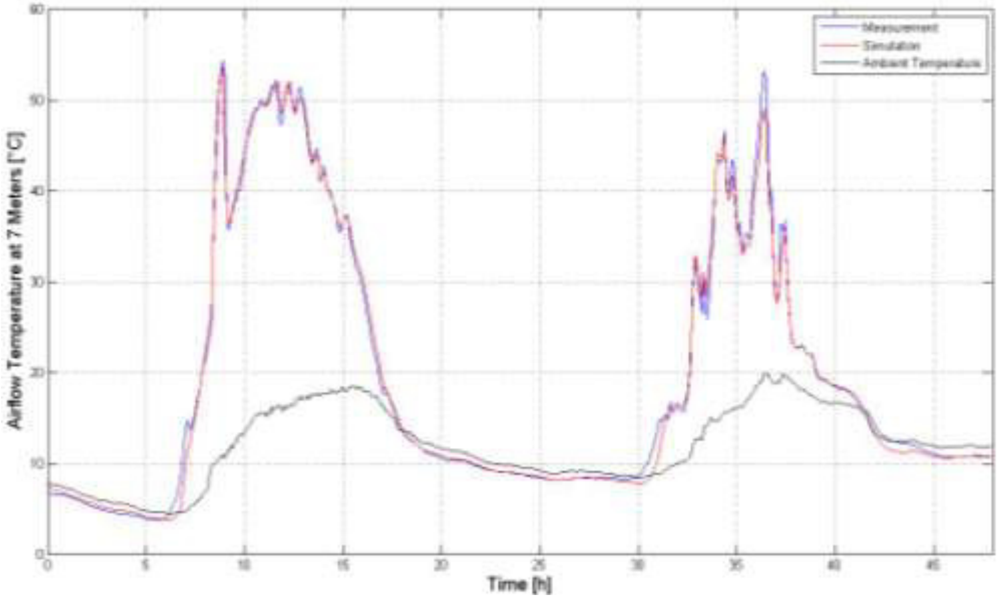

Fig. 5. Simulation of the underflow-collector prototype from 21 to 22 March 2005.

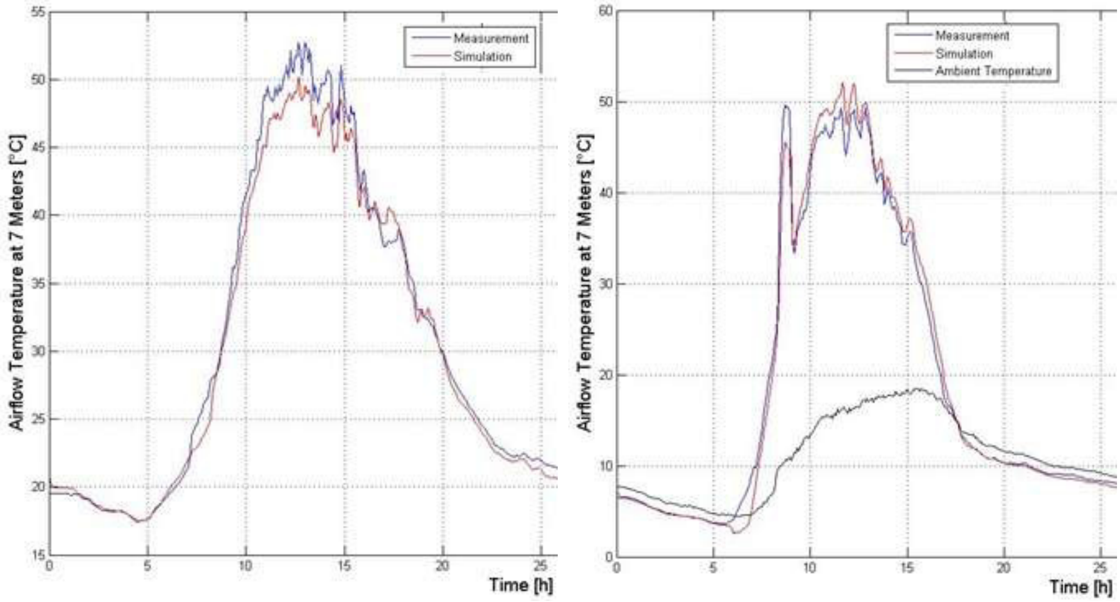

Fig. 6. (a) Simulation of the uncovered-underflow-collector prototype at 20.06. 2005; (b) Simulation of the overflow-collector prototype at 21.03.2005.

It is important to remember that the simulations are taking into account airflow leakages; otherwise the simulated temperatures would be a bit lower. Besides it, some parameters were determined for the simulation, and it is known that the measurements contain some degree of uncertainty. Nevertheless, in general, the blocks´ performances of the solar air collector were successfully verified against experimental data from the prototypes.

In order to improve the performance of the blocks of solar air collector, further steps could be made:

- To analyze more simulations and result comparisons of the blocks of collector against other real collector prototypes.
- To try other empirical equations of convection heat transfer coefficients in the models.
- To write the collector models in a programming language such as S-functions (system functions) in language C, Fortran or Ada amongst others, instead of the block subsystems.

Nevertheless, the temperature comparisons showed that the blocks of collector models are able to keep the thermal behavior of a real collector in operation. Therefore, the blocks of solar air collector can be useful to gain an insight into the collectors themselves and into air-heating systems.

Acknowledgements

I am thankful to Solar Institute Jülich, Dipl.-Ing. Klaus Backes, B.Sc. Sebastian Krumscheid and Dr. Marcelo Lopes.

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